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DESIGN CRITERIA FOR FRANGIBLE COVERS IN ORDNANCE FACILITIES

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1.0 PURPOSE

This paper presents preliminary design criteria for frangible surfaces intended to "break-up" and "blow-away" quickly enough to limit the internal blast environment, structural damage and exterior debris hazard from explosions inside structures. The design criteria relate the critical design parameters of the structure, frangible surface and explosive to the internal loading -- in a format that facilitates the design of frangible covers and the prediction of internal blast loads.

2.0 BACKGROUND

2.1 Internal Explosions

Shock Pressures. Consider an explosion inside a hardened building with a frangible cover as illustrated in Figures 1 and 2. The detonation generates shock waves. The initial wave strikes the frangible cover, and all other interior surfaces, and is reflected. The energy in the reflected wave depends, in part, on the physical characteristics of the reflecting surface. When the incident wave first strikes the frangible cover, the pressure in the incident wave is shocked up to a reflected pressure. If this pressure accelerates the cover fast enough then the relative velocity between the incident shock wave and cover decreases. This reduces the total energy (total impulse) in the reflected wave to a value less than if instead the cover was non-frangible. In any case, the reflected waves, bouncing back and forth between the walls, floor and roof, produce a shock pressure loading on interior surfaces of the structure. The contribution from the cover to the total shock impulse on other interior surfaces depends, to a large degree, on the number of covers, cover size (surface area and aspect ratio), location of cover

relative to the explosive, physical properties of the cover (mass, strain energy capacity and failure mode) and boundary conditions of the cover (resistance of supports to moment, shear and tension).

The Naval Surface Weapons Center is currently developing criteria to predict the reflected-shock impulse on covers and the effects of cover characteristics on the reflected-shock impulse applied to other interior surfaces of a structure. At this point in the study it appears that for the practical range of design parameters, covers experience the full-reflected-shock impulse. Further, covers should be considered non-frangible surfaces when computing the reflected shock impulse on other interior surfaces of the structure.

Gas Pressures. If the explosion is confined inside an enclosed space, such as a building, the heat released by the detonation and the subsequent after-burning raises temperatures of the air and gaseous by-products of the explosion. This phenomenon generates gas pressures, in addition to shock pressures, in the same time period. The gas pressure inside the structure rises to some peak value, the value depending on the ratio of the net explosive weight to volume of the structure. The gas pressure then gradually decays as gas temperatures drop and gases vent from the structure. The gases vent through openings created by breakage of building components, such as windows, doors and frangible covers.

The peak gas pressure is characteristically small compared to the peak reflected-shock pressure. However, the duration of the gas pressures can be many times greater than the duration of the reflected-shock pressures, especially when the vent area is small compared to the volume of the structure. Progressive breakup of the building increases the total vent area. This increases the rate of escaping gases which, in turn, increases the rate of decay in gas pressures, and thus, decreases the duration of the gas pressure.

Blast hardened or massive structures often have little or no inherent excape paths for gases. In such cases, vent areas must be built into the structure. In practice, these vent areas are openings with frangible covers. The frangible covers are intended to breakup and blow away

quickly enough to reduce the gas pressure environment inside the structure. This strategy reduces the extent of structural damage and secondary debris.

2.2 Frangible Covers

Frangible covers are especially important in hardened structures that contain explosives. For example, safety standards may require a hardened structure to protect its inhabitants and contents from effects of possible explosions located outside the structure. Typically, such structures are massive and capable of absorbing large amounts of internal strain energy. Consequently, the benefits of protection provided against effects from an external explosion may be more than offset by the increased risk to inhabitants and contents from an internal explosion. Further, explosions in hardened structures increase the risk to nearby facilities since the greater blast loads inside a hardened structure produce greater launch velocities of flying debris threatening nearby facilities. A compromise solution to this dilemna is to install one or more frangible covers in exterior surfaces of the structure. The covers are placed at strategic locations that do not compromise protection from effects of an external explosion. The frangible covers reduce the internal blast environment and thus the external debris hazard.

Ordnance test structures, such as missile test cells, are also frequently blast hardened, especially if the test cell is immediately adjacent to the Weapons Maintenance Building that supports test operations. For this case, the test cell is blast hardened to reduce blast and debris on the adjoining building. Typically, one wall of the test cell is made frangible to relieve internal blast loads and focus explosion effects in prescribed directions outside the structure.

3.0 PROBLEM

The NAVFAC P-397 (Ref 1) states that "although frangibility is imperfectly understood and difficult to measure, it has been assumed that a material whose weight is 10 psf of surface area or less may be

considered frangible for both the shock-front pressures and gas pressures resulting from detonation of explosives greater than 100 lbs." NAVFAC P-397 further states "if a large portion (one or more surfaces) of a structure whose weight is greater than 10 psf fails, then this surface of the structure is considered frangible for the gas pressures. However, because the heavier surface will take longer to fail than the lighter surfaces, full reflection of the shock pressures will occur." In design practice, this criteria is interpreted to mean that any surface less than 10 psf is fully frangible, i.e., the surface does not contribute shock impulse to other interior surfaces of the structure and the degree of venting for gases is the same as if no surface covered the opening. This interpretation may contribute large errors in the design process and result in unsafe designs.

Trends in safety regulations require less risk to exposed individuals in ordnance facilities. This trend demands a better understanding of frangibility. For example, recent changes in NAVSEA OP-5 (Ref 2) require personnel working in a missile test cell to be exposed to no more than 2.3 psi from effects of possible explosions in other test cells. This requirement is difficult to satisfy in a multiple test cell complex. The facility designer desires one wall to be frangible in order to reduce the internal blast environment from an internal explosion, thereby, lowering the MCON cost of the facility and external debris hazard. However, to protect personnel in that cell from explosions in other cells, the designer must strengthen the frangible wall to safely resist external blast pressures. But strengthening the wall invariably results in a massive wall which violates current frangibility criteria. The solution to this dilemma usually requires severe restrictions of test operating procedures and lower production levels. Strengthening the "frangible" wall is the practical and cost effective solution, provided the designer has design criteria which account for effects of wall mass on internal blast environment.

The same problem is faced in trying to satisfy physical security regulations. A massive wall is desired to increase the denial time to forced intrusion into a missile test cell, but a light wall is required

to control construction costs. Again, physical security requirements must be compromised because of a lack of criteria on effects of wall mass on internal blast environment.

In view of the problems cited above, the Naval Civil Engineering Laboratory has undertaken a study to refine design criteria for frangible surfaces. The work is being sponsored by the Department of Defense Explosives Safety Board. The criteria presented herein is preliminary and requires further test validation.

4.0 SOLUTION FORMULATION

Consider an explosion inside either the missile test cell or the building shown in Figure 2. An opening of area A is located in one surface of either structure. The opening is covered with a frangible panel. The panel has a mass γ, area A and dimensions ℓ by h. The normal distance from explosive W to the panel is R.

The blast loading (combined shock plus gas pressure-time history) acting on an interior surface of the box is shown in Figure 3. This is also the blast loading on a cover placed over the opening provided the cover is non-frangible for shock pressures (i.e., the cover provides full-reflection of all shock waves striking its surface), but fully frangible for gas pressures (i.e., the cover does not decrease the vent area, A, for escaping gases; the vent area is A from the instant of detonation).

4.1 Shock Pressure Loading

If the reflected-shock pressure on the cover at any time t is P_r (t) then the total reflected-shock impulse, i_r, is

$$\frac{i_r}{W^{1/3}} = \int_0^{T_r} \frac{P_r(t)}{W^{1/3}}\, dt \quad \text{,solution obtained from NAVFAC P-397} \qquad (1)$$

The solution of Equation 1 is obtained from charts presented in NAVFAC P-397 (Ref 1). The charts predict the average reflected-shock impulse applied to a prescribed surface of a box-shaped structure. The charts are based on analytical procedures and empirical data derived from explosives tests. The P-397 procedure involves entering appropriate charts with a series of dimensionless parameters related to the geometry and size of the structure and the location of the explosive. The parameters are the length, L, and height, H, of the box-surface of interest; net weight of explosive, W; number of adjacent reflecting surfaces, N; normal distance from charge to box-surface of interest, R; distance from charge to nearest adjacent reflecting surface, ℓ_1; and the height of the explosive, h_1.

The accuracy of the P-397 value for i_r depends on the size of the cover relative to the size of the face of the box. The predicted value of i_r is the average value for the entire face of the box, including the area of the cover. Consequently, the procedure may underestimate i_r applied to the frangible cover if the area of the cover is small compared to the total area of the face of the box. In this case, computer programs, such as BARCS (Ref 3), should be used to estimate i_r. BARCS outputs i_r at each node point of a mesh simulating the surface area of the box. The proper value of i_r for the cover is the value of i_r averaged over nodal points within the area of the cover.

4.2 Gas Pressure Loading

4.2.1. Fixed Vent Area. Given a constant vent area, A, and the time constant, α, describing the rate of exponential decay in pressure, the gas pressure, P_g, inside the box at any time, t, is:

$$P_g(t) = B_g \left(1 - \frac{t}{T_g}\, e\right)^{-\alpha(t/T_g)} \tag{2}$$

According to analytical work by Proctor and Filler (Ref 4) and explosives tests by NCEL (Ref 5), the peak gas pressure, B_g, inside the box is

a function of the ratio W/V, the explosive weight, W, relative to the volume of the box, W. The relationship between B_g and W/V is plotted in Figure 4.

$$B_g = f\ (W/V), \qquad \text{from Figure 4.} \tag{3}$$

Based on explosives tests by Keenan and Tancreto (Ref 5), the scaled duration of the gas pressure, $T_g/W^{1/3}$, inside the box for a constant vent area, A, and box volume, V, is:

$$\frac{T_g}{W^{1/3}} = 2.26 \left(\frac{A}{V^{2/3}}\right)^{-0.86} \left(\frac{W}{V}\right)^{-0.86} \quad \text{, provided A \& V = constant} \tag{4}$$

and the corresponding scaled total impulse of the gas pressure, $i_g/W^{1/3}$, is:

$$\frac{i_g}{W^{1/3}} = 569 \left(\frac{A}{W^{2/3}}\right)^{-0.78} \left(\frac{W}{V}\right)^{-0.38} \quad \text{, provided A \& V = constant} \quad A/V^{2/3} \leq 0.21 \tag{5}$$

Equations 4 and 5 are empirical relationships derived from the gas pressure-time history measured inside a box with A, V and W held constant in each test but varied between tests. In these tests, pressure measurements indicated no gas pressure developed inside the box for $A/V^{2/3} \geq 0.60$.

$$\frac{i_g}{W^{1/3}} = 0 \quad \text{, provided A = constant} \quad A/V^{2/3} \geq 0.60 \tag{6}$$

No test data is available to derive the expression for $i_g/W^{1/3}$ where $0.21 < A/V^{2/3} > 0.60$. However, for the purpose of this paper it is arbitrarily assumed that the log of $i_g/W^{1/3}$ varies linearly with the log of $A/V^{2/3}$ for $0.21 \leqq A/V^{2/3} \leq .60$.

Given A, V and W it is possible to derive an explicit expression for the time constant, α, based on the following requirement.

$$i_g = \int_o^{T_g} P_g(t)\, dt \tag{7a}$$

Combining Equations 2 and 7a

$$i_g = B_g \int_o^{T_g} \left(1 - \frac{t}{T_g} \quad e\right)^{-\alpha(t/T_g)} dt \qquad \text{,provided A\&V = constant} \tag{7}$$

where B_g, T_g and i_g are fixed values obtained from Equations 3, 4, and 5 (or 5a), respectively, based on given values of A, V and W.

4.2.2 Variable Vent Area. Consider a frangible cover over an opening in a structure containing an explosion as shown in Figure 3. The combined shock and gas pressures force the cover to move away from the opening. This motion results in a variable vent area that increases with time. Calculation of the gas pressure history inside the structure requires an iterative process because of the variable vent area. The iterative process proceeds as follows.

Refering to Figures 5 and 6, at time t_i the known gas pressure is P_i and the known acceleration, velocity and displacement of the cover, acting as a rigid plate, are $\ddot{x}_i$, $\dot{x}_i$ and x_i, respectively. If P_{i+1} is the assumed gas pressure at time t_{i+1}, then

$$\begin{aligned}
t_{i+1} &= t_i + \Delta t \\
\ddot{x}_{i+1} &= P_{i+1}/m \\
\dot{x}_{i+1} &= \dot{x}_i + (\ddot{x}_i + \ddot{x}_{i+1})(\Delta t)/2 \\
x_{i+1} &= x_i + \dot{x}_i\, \Delta t + (\ddot{x}_i + \ddot{x}_{i+1})(\Delta t)^2/4
\end{aligned} \tag{8}$$

During the time interval Δt, the average displacement of the cover is $(x_i + x_{i+1})/2$. If the perimeter of the opening is s, then the average vent area, $\bar{A}_{i+1}$, available for gases to escape from the structure is

$$\bar{A}_{i+1} = (x_i + x_{i+1})s/2 \tag{9}$$

Considering $\bar{A}_{i+1}$ to be a fixed vent area during the time interval, Δt, the gas pressure impulse, i_g, is calculated from Equation 5, the gas pressure duration, T_g, is calculated from Equation 4, and the time constant, α, is calculated from Equation 7. Knowing α_{i+1}, the gas pressure, P_{i+1} at time t_{i+1} is calculated from Equation 2. The calculated value of P_{i+1} becomes the new assumed value of P_{i+1} and the above process is repeated until the difference between the assumed and computed values of P_{i+1} is within a prescribed error limit. Given agreement, time is incremented by Δt and the entire process is repeated for the next time step. If during this process, $\bar{A}$ becomes equal to the area of the opening, then the effective vent area is fixed and $\bar{A} = A$ for all succeeding time intervals.

Eventually, the gas pressure decays to zero. The time corresponding to this point is the gas duration, T_g, inside the structure, and the total gas impulse, i_g, is equal to the total area under the gas pressure-time curve. The above computational process was the basis for NCEL computer program REDI which was used to develop design criteria for frangible covers.

5.0 DESIGN CRITERIA

Computer program REDI was used to generate design criteria for frangible covers. The following criteria are considered preliminary and require further test validation.

5.1 Gas Impulse

Criteria for the gas pressure impulse inside a structure with a frangible cover are presented in Figures 7-10. In each figure, the scaled gas pressure impulse, $i_g/W^{1/3}$, is plotted as a function of the scaled vent area, $A/V^{2/3}$, for several values of the frangible cover mass, $\gamma/W^{1/3}$. Each family of curves in Figures 7-10 are for fixed values of the scaled reflected shock impulse, $i_r/W^{1/3}$, acting on the frangible cover and the ratio of the net explosive weight to structure volume, W/V. The

curves assume the total reflected shock impulse, i_r, is applied to the cover at time t = 0, i.e. the reflected shock impulse imparts an initial velocity to cover equal to i_r/m where m is the mass per unit surface area of the cover. This assumption reduced significantly the number of parameters required to display the design criteria.

Use of the criteria require interpolat_on between values corresponding to the curves in Figures 7-10. Linear interpolation on a log-log scale is recommended for obtaining an intermediate value of any parameter, using either mathematical relationships or log-log graph paper. Further, it is recommended that i_r in Figures 7-10 be interpreted as the value predicted by procedures outlined in NAVFAC P-397 or computer program BARCS (Ref 3).

5.2 Peak Gas Pressure

As stated earlier, the peak gas pressure, B_g, depends on the ratio of the net explosive weight to structure volume, W/V, and is obtained from Figure 4.

$$B_g = f\ (W/V), \qquad \text{from Figure 4} \tag{3}$$

5.3 Effective Gas Duration

The effective duration of the gas pressure based on a linear time decay in the pressure' is

$$T'_g = \frac{2\ i_g}{B_g} \tag{10}$$

where i_g is the total gas pressure impulse obtained from Figures 7-10 and B_g is the peak gas pressure obtained from Equation 3.

6.0 TEST VALIDATION

6.1 Method of Validation

Experimental data obtained from explosive tests designed to evaluate the performance of earth covered structures was used to validate the design criteria for frangible covers shown in Figures 7-10. The experiment involved detonating explosives inside a series of small earth-covered missile test cells having one frangible wall and a soil-covered roof slab. The frangible wall and roof slabs were not fastened to their supports. Test variables were the mass of the frangible wall, γ, mass of the soil covered roof, $\gamma_s + \gamma_r$, and weight of explosive, W. The motion of the roof and wall slabs was measured in each test with a high speed camera.

The total reflected-shock plus gas impulse, i_T, imparted to the roof was derived from the measured maximum vertical displacement of the roof slab, x_m, by applying the principle of conservation of energy. Since the roof is unrestrained, the total work done by the gravity forces of the roof must equal the total change in its kenetic energy.

$$\text{Work} = -(\gamma_s + \gamma_r)\, x_m \tag{11a}$$

Since $\dot{x} = 0$ at $x = x_m$, the total change in kinetic energy, ΔKE, is

$$\Delta KE = \frac{1}{2}\left(\frac{\gamma_s + \gamma_r}{g}\right)\left(0^2 - \dot{x}_T^{\,2}\right) \tag{11b}$$

Equating Equations 11a and 11b,

$$y_m = \frac{\dot{x}_T^{\,2}}{2\,g} \tag{11c}$$

From the principle that the total impulse applied to the roof must equal the change in its momentum,

$$\int_0^T P(t)\,dt = \left(\frac{\gamma_s + \gamma_r}{144\ g}\right)\left(\dot{x}_T - 0\right)$$

$$i_T = \left(\frac{\gamma_s + \gamma_r}{144\ g}\right)\ \dot{x}_T \tag{11d}$$

Combining Equations 11c and 11d and dividing the result by $W^{1/3}$, the scaled total impulse of the reflected-shock plus gas impulse on the roof is:

$$\frac{i_T}{W^{1/3}}\ \text{(measured)} = 1.731\left(\frac{\gamma_s + \gamma_r}{W^{1/3}}\right)\ \sqrt[2]{x_m} \tag{11}$$

Since γ_s, γ_r, W, and x_m are known values for each test, the scaled total impulse applied to the roof was calculated from Equation 11. This value was considered to be the "measured" value of $i_T/W^{1/3}$ acting on the roof of the missile test cell.

The predicted value of $i_T/W^{1/3}$ was taken to be the sum of the scaled reflected-shock impulse, $i_r/W^{1/3}$, predicted from criteria presented in NAVFAC P-397 (which is based on the parameters shown in Figure 3), plus the scaled gas impulse, $i_g/W^{1/3}$, predicted from the criteria presented in Figures 7-10. In other terms, the predicted scaled total impulse acting on the roof of the missile test cell was taken as:

$$\frac{i_T}{W^{1/3}}\ \text{(predicted)} = \frac{i_r}{W^{1/3}}\ \text{(NAVFAC P-397)} + \frac{i_g}{W^{1/3}}\ \text{(Fig. 7-10)} \tag{12}$$

The predicted value of $i_r/W^{1/3}$ in Equation 12 assumed four reflecting surfaces (N=4), i.e., the frangible wall, in addition to the other three walls, was considered to be a non-frangible surface for shock waves striking its surface. The difference between $i_T/W^{1/3}$ obtained from Equations 11 and 12 was the basis for validating the reliability of the design criteria for frangible covers presented in Figures 7-10.

6.2 Test Description

Design details of the test structure are shown in Figure 11. The structure was a one-sixth geometric-scale model of a HARPOON missile test cell. The floor, sidewalls, backwall and floor were constructed from 3-inch-thick steel plate, joined together with full-penetration welds. The backwall had no door opening. The bottom face of the floor was flush with the ground surface.

The roof slab was 1-1/8-inch-thick plywood (3.3 psf) with No. 10 gauge sheet metal (5.63 psf) nailed to the inside face. The roof slab was covered with sand to depth, d_s, in a berm-like fashion. The berm was configured so that the soil depth, d_s, extended a distance d_s beyond the vertical extension of the walls, except at the headwall. The surface of the berm was spray painted white to improve photographic contrast in recording the failure mechanism of the earth-bermed roof. The total roof mass was varied between tests by changing the depth of sand, d_s.

The test charge was Composition C-4 explosive shaped into a right cylinder with a length-diameter ratio equal to 1.0. The charge was positioned midway between the walls and 7 inches above the floor, the typical scaled location of a HARPOON missile during a testing operation The test charge ranged from W = 1.0 to 3.0 lbs which corresponds to approximately W = 216 and 640 lbs full-scale, respectively.

The frangible wall was absent in two tests. In all other tests, the frangible wall was either 1-1/8-inch plate glass (one test) at $\gamma = 1.64$ lb/ft^2, or 3/8-inch plywood with 28 gauge sheet metal on the inside face (6 tests) at $\gamma = 1.73$ lb/ft^2 or 1.0-inch plywood with 13 gauge sheet metal on both faces (two tests) at $\gamma = 10.50$ lb/ft^2. Based on scaling laws, $\gamma = 1.73$ and 10.50 lb/ft^2 are equivalent to $\gamma = 10.38$ and 63.0 lb/ft^2 full-scale, respectively.

A view of a typical test setup prior to detonation is shown in Figure 12. Note the adhesive tape used to secure the frangible wall to its supports. Also note the soil berm spray painted white.

The values of critical parameters for each test are presented in Table 1. Note: The listed values of γ_s and γ_r have been increased by

9% to account for a 2-inch overlap of the roof slab onto each wall. Further, γ for the frangible wall has been increased by 5% to account for a 1/2-inch overlap of the wall onto its supports.

6.3 Predicted Versus Measured Results

The measured and predicted results for each test are compared in Table 2. The small difference between the measured and predicted $i_T/W^{1/3}$ for tests 23 and 24 (no frangible wall, i.e. N=3) indicate the NAVFAC P-397 procedure for the predicting the reflected-shock impulse on interior surfaces of a structure are quite accurate, at least for the range of parameters tested.

The value of test parameters in tests 25 and 27 are nearly identical, except for the properties of the frangible wall. The frangible wall was plate glass in test 25 and plywood/metal in test 27. The small difference between measured and predicted $i_T/W^{1/3}$ for these tests suggests that the brittleness of a frangible wall does not significantly effect the gas pressure environment inside a structure.

Test 29 provides the best measure of the reliability of the design criteria since the gas impulse was a large percentage of the total impulse. Note that the difference between the measured and predicted i_T is largest for this test.

The ratio of measured to predicted i_T averaged over all tests is 0.99. This suggests that the design criteria for frangible covers is adequate, at least for the range of parameters tested.

7.0 APPLICATION OF CRITERIA

The following problems and their solutions illustrate the application of the design criteria for frangible covers.

7.1 Missile Test Cell

The missile test cell shown in Figures 1 and 2 supports testing and checkout of the LUNI missile. The net weight of explosive for the LUNI is 343 pounds TNT equivalent. The center of gravity of the explosive is positioned such that the scaled reflected-shock impulse on the frangible wall is $i_r/W^{1/3} = 100$ psi-msec/lb$^{1/3}$, according to NAVFAC P-397 (or computer program BARCS). The frangible wall is a 3-inch-thick reinforced concrete slab with a total surface area equal to 150 ft^2. The volume of the missile test cell is 8575 ft^3.

(a) Problem: Find the peak gas pressure, B_g, gas impulse, i_g, and effective gas duration, T'_g, inside the missile test cell.

Solution: The scaled area and mass of the frangible wall and the density of explosive in the missile test cell are

$$A/V^{2/3} = 150/(5277)^{2/3} = 0.49$$

$$\gamma/W^{1/3} = (3 \times 145)/12)/(343)^{1/3} = 5.2 \text{ psf/lb}^{1/3}$$

$$W/V = 343/5277 = 0.040 \text{ lb/ft}^3$$

Entering Figure 4 with $W/V = 0.040$, find

$$B_g = 240 \text{ psi}$$

Entering Figure 9 with $W/V = 0.040$, $\gamma/W^{1/3} = 5.2$, $A/V^{2/3} = 0.49$ and $i_r/W^{1/3} = 100$, find

$$i_g/W_{1/3} = 325 \text{ psi-msec/lb}^{1/3}$$

$$i_g = 325(343)^{1/3} = 2275 \text{ psi-msec}$$

From Equation 10, the effective gas duration for design purposes is

$$T'_g = \frac{2\, i_g}{B_g} = \frac{2(2275)}{240} = 19.0 \text{ msec}$$

(b) Problem: Find the percent reduction in the gas impulse if the LUNI missile is moved closer to the frangible wall such that $i_r/W^{1/3}$ = 1000 psi-msec/lb$^{1/3}$.

Solution: Entering Figure 9 with W/V = 0.040, $\gamma/W^{1/3}$ = 5.2, $A/V^{2/3}$ = 0.49 and $i_r/W^{1/3}$ = 1000, find

$$i_g/W^{1/3} = 92 \text{ psi-msec/lb}^{1/3}$$

$$i_g = 92\ (342)^{1/3} = 644 \text{ psi-msec}$$

Therefore, the reduction in gas impulse applied to all surfaces of the missile test cell is

$$\text{Reduction in } i_g = \left(\frac{2275 - 644}{2275}\right) 100 = 72\%$$

This reduction in i_g will reduce significantly the construction cost of the missile test cell but increase significantly the possible strike range of debris from the frangible wall which is roughly proportional to the square of the total impulse. For example,

$$i_T = i_r + i_g = 100(343)^{1/3} + 2275 = 2975 \text{ psi-msec} \quad \text{(problem a)}$$

$$i_T = i_r + i_g = 1000(343)^{1/3} + 644 = 7644 \text{ psi-msec} \quad \text{(problem b)}$$

Therefore, without an exterior barricade in front of the frangible wall, the possible increase in the strike range of debris, R_s, is

$$\frac{R_s \text{ (problem a)}}{R_s \text{ (problem b)}} = \left(\frac{7644}{2975}\right)^2 = 6.6$$

7.2 Weapons Maintenance Building

The weapons maintenance building shown in Figures 1 and 2 is for maintenance of the HARPOON missile. The workbay, shown in Figure 2, is 100 feet long, 40 feet wide, and 20 feet high and contains no more than 2400 pounds TNT equivalent at any one time. The roof and walls are

massive reinforced concrete slabs designed to protect operating personnel from an inadvertent explosion in an unrelated ordnance facility located nearby. A large equipment door at both ends of the workbay is 25 feet long and 15 feet high. The doors are not blast-hardened and weigh 13.3 psf.

(a) Problem: Find the peak gas pressure, B_g, gas impulse, i_g, and effective gas duration, T'_g, if the scaled reflected-shock impulse, $i_r/W^{1/3}$, on the doors is 100 psi-msec/lb$^{1/3}$.

Solution: The door area is A = (25 x 15)2 = 750 ft^2. The volume of the workbay is V = 40 x 20 x 100 = 80,000 ft^3. The weight of explosive is W = 2400 lb. The door mass is γ = 13 psf. Therefore, the critical scaled parameters are

$$A/V^{2/3} = 750/(80{,}000)^{2/3} = 0.40$$

$$W/V = 2400/80{,}000 = 0.040 \text{ lb/ft}^3$$

$$\gamma/W^{1/3} = 13.3/(2400)^{1/3} = 1.00 \text{ psf/lb}^{1/3}$$

Entering Figure 9 with these values, find

$$i_g/W^{1/3} = 120; \quad i_g = 120(2400)^{1/3} = 1606 \text{ psi-msec}$$

Entering Figure 4 with W/V = 0.040, find

$$B_g = 240 \text{ psi}$$

From Equation 10, the effective duration of gas pressure in the workbay is

$$T'_g = 2(1606)/240 = 13.4 \text{ msec}$$

(b) Problem: Find the gas impulse in the workbay if the mass of the equipment doors is increased to 67 psf to improve physical security of the building.

Solution: The scaled door mass in $\gamma/W^{1/3} = 67(2400)^{1/3} = 5.0$ psf/lb$^{1/3}$. Entering Figure 9, find

$$i_g/W^{1/3} = 350; \quad i_g = 350(2400)^{1/3} = 4686 \text{ psi-msec}$$

Thus, increasing the door mass from 13.0 to 67 psf increases the gas impulse applied to interior surfaces of the building by

$$\text{increase in } i_g = \left(\frac{4686 - 1606}{1606}\right) 100 = 192\%$$

8.0 FUTURE WORK

Explosive tests are planned for 1983. The tests will extend the range of test parameters and include large scale tests. The large scale tests are considered important since the theory used to develop the design criteria is based on empirical relationships derived from small scale tests.

9.0 REFERENCES

1. Naval Facilities Engineering Command. NAVFAC P-397, Army TM 5-1300 and Air Force AFM 88-22: Structures to resist the effects of accidental explosions. Washington, D.C., Jun 1969.

2. Naval Sea Systems Command. NAVSEA OP-5: Ammunition and explosives ashore, vol 1, rev. 5. Washington, D.C., Oct 1976.

3. Civil Engineering Laboratory. Technical Note N-1494: Optimum dynamic design of nonlinear reinforced concrete slabs under blast loading, by J. M. Ferritto. Port Hueneme, Calif., Jul 1977.

4. J. F. Proctor and W. S. Filler. "A computerized technique for blast loads from confined explosions," from Minutes of the 14th Annual Explosives Safety Seminary, New Orleans, La., Nov 1972, p 99.

5. Civil Engineering Laboratory. Technical Report R-828: Blast environment from fully and partially vented explosions in cubicles, by W. A. Keenan and J. E. Tancreto. Port Hueneme, Calif., Nov 1975.

10.0 LIST OF SYMBOLS

A	Area of the opening without the frangible cover, ft^2
$\bar{A}$	xp, effective vent area, ft^2
B_g	Peak gas pressure extrapolated to time $t = 0$, psi
B_r	Peak reflected-shock pressure, psi
d_s	Depth of soil cover, ft
$E(x)$	Total strain energy absorbed by structural element at displacement x relative to its support, ft-lb/ft^2
g	Gravity = 32.2×10^{-6}, ft/$msec^2$
h	Height of frangible wall, ft
h_1	Height of explosive (c.g.) above floor, ft
i_B	Total reflected shock impulse, psi-msec
i_g	Total gas impulse, psi-msec
i_r	Total reflected-shock impulse, psi-msec
i_T	Total impulse; sum of reflected-shock plus gas impulses, psi-msec
ℓ	Length of frangible wall, ft
ℓ_1	Distance from explosive (c.g.) to sidewall, ft
m	Mass per unit area of surface, psf-$msec^2$/ft
N	Number of adjacent reflecting surfaces.
$P(t)$	Pressure at time t, psi
$P_g(t)$	Gas pressure at any time t, psi
$P_r(t)$	Reflected-shock pressure at any time t, psi
R	Normal distance from c.g. of explosive to a surface of structure, ft
s	Perimeter of the opening providing escape path for gases, ft
T_g	Duration of gas pressure, msec
T'_g	$2i_g/B_g$ = Effective duration of the gas pressure based on a linear time decay, msec

t	Elapsed time after detonation, msec
t_1	Time when reflected pressure equals the gas pressure, msec
T_r	$2i_r/B_r$ = Effective duration of the reflected shock pressure based on a linear time decay, msec
V	Volume of structure containing the explosion, ft^3
W	Net weight of explosive, lb (TNT equivalent)
x	Displacement at any time t, ft
$\dot{x}$	Velocity at any time t, ft/msec
x_m	Maximum displacement, ft
$\dot{x}_T$	Velocity at time T_r, ft/msec
α	Exponential decay constant for $P_g(t)$, $msec^{-1}$
γ	Mass of frangible cover per unit area of surface, lb/ft^2
γ_r	Mass of roof slab per unit area of surface, lb/ft^2
γ_s	Mass of soil cover per unit area of surface, lb/ft^2
ρ_s	Density of soil, lb/ft^3

Table 1. Test Parameters for Missile Test Cell

Test No.	Test Charge				Test Cell[a]				Frangible Wall				
	W (lb)	R (ft)	h_1 (ft)	ℓ_1 (ft)	d_s (ft)	ρ_s (lb/ft^3)	γ_s[b] (lb/ft^2)	γ_r[b] (lb/ft^2)	h (ft)	ℓ (ft)	P (ft)	A (ft^2)	γ[c] (lb/ft^2)
23	1.00	3.00	0.583	1.833	0.667	85.0	61.8	9.73	2.58	3.75	12.3	9.17	0.00
24	3.00	3.00	0.583	1.833	0.833	84.9	77.1	9.86	2.58	3.75	12.3	9.17	0.00
25	1.00	3.00	0.583	1.833	0.667	87.5	63.6	9.73	2.58	3.75	12.3	9.17	1.72
26	1.00	3.00	0.583	1.833	0.833	89.0	80.8	9.73	2.58	3.75	12.3	9.17	1.82
27	1.00	3.00	0.583	1.833	0.667	85.8	62.4	9.04	2.58	3.75	12.3	9.17	1.82
28	3.00	3.00	0.583	1.833	1.000	83.0	90.5	9.04	2.58	3.75	12.3	9.17	11.03
29	1.00	3.00	0.583	1.833	0.833	84.2	76.5	9.86	2.58	3.75	12.3	9.17	11.03
30	3.00	3.00	0.583	1.833	1.000	84.0	91.6	9.86	2.58	3.75	12.3	9.17	1.82
31	3.00	3.00	0.583	1.833	0.833	84.6	76.8	9.86	2.58	3.75	12.3	9.17	1.82
32	1.00	3.00	0.583	1.833	0.333	84.6	30.7	10.0	2.58	3.75	12.3	9.17	1.82
33	3.00	3.00	0.583	1.833	0.333	85.0	30.9	10.0	2.58	3.75	12.3	9.17	1.82

[a] $V = 55.1\ ft^3$; $L = 6.0$ ft; $H = 2.50$ ft; $w = 3.67$ ft.

[b] γ_s and γ_r increased by 9% to account for overlap of roof slab onto its supports.

[c] γ increased by 5% to account for overlap of frangible wall onto its supports.

Table 2. Comparison of Measured and Predicted Total Impulse on Roof

Test No.	Scaled Parameters				Measured		Predicted			i_T(meas.) / i_T(pred.)
	$A/V^{2/3}$ (-)	$R/W^{1/3}$ ($ft/lb^{1/3}$)	W/V (lb/ft^3)	$\gamma/W^{1/3}$ (lb/ft^2-$lb^{1/3}$)	y_m (ft)	$i_T/W^{1/3}$[a] (psi-msec/$lb^{1/3}$)	$i_r/W^{1/3}$[b] (psi-msec/$lb^{1/3}$)	$i_g/W^{1/3}$[c] (psi-msec/$lb^{1/3}$)	$i_T/W^{1/3}$[d] (psi-msec/$lb^{1/3}$)	
23	0.633	3.17	0.018	0.0	2.4	192	161	0	161	1.19
24	0.633	2.20	0.054	0.0	6.4	264	253	0	253	1.04
25	0.633	3.17	0.018	1.72	4.4	266	198	100	293	0.89
26	0.633	3.17	0.018	1.82	4.2	321	198	105	297	1.06
27	0.633	3.17	0.018	1.82	5.4	287	198	105	297	0.95
28	0.633	2.20	0.054	1.26	~9.8	374	311	61	410	1.01
29	0.633	3.17	0.018	11.03	9.5	461	198	368	540	0.81
30	0.633	2.20	0.054	7.64	--	--	311	237	548	--
31	0.633	2.20	0.054	1.26	--	--	311	59	370	--
32	0.633	3.17	0.018	1.82	--	--	198	99	297	--
33	0.633	2.20	0.054	1.26	55	364	311	61	370	0.98

Avg. = 0.99

[a] From Equation 11.

[b] From Equation 1 based on N = 3 for tests 23 & 24 and N = 4 for tests 25-33.

[c] From Figures 7-10.

[d] From Equation 12.

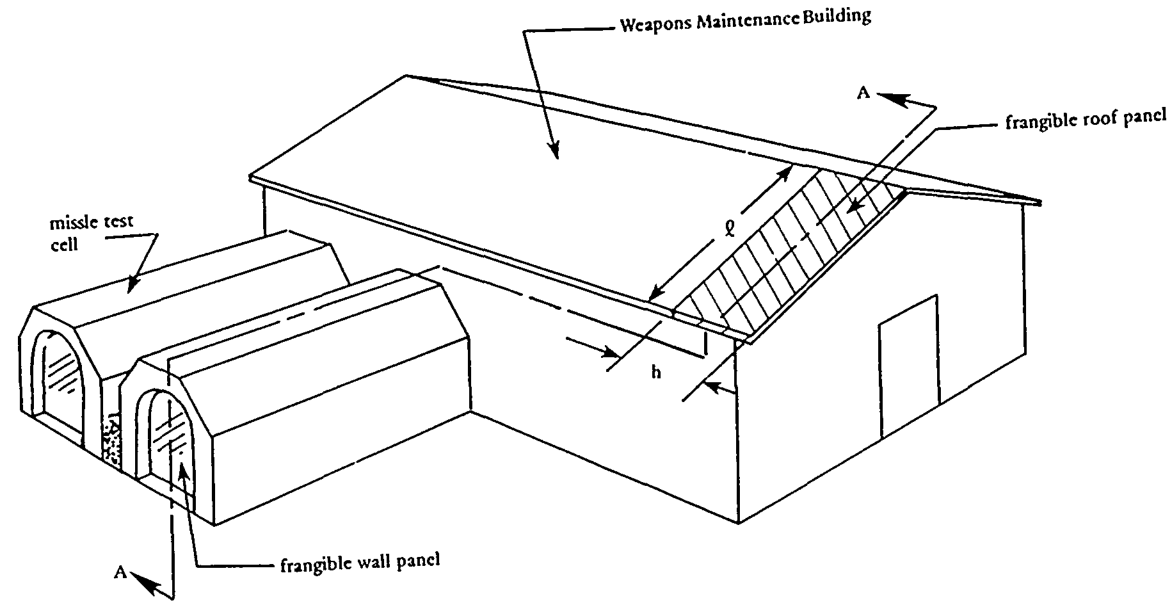
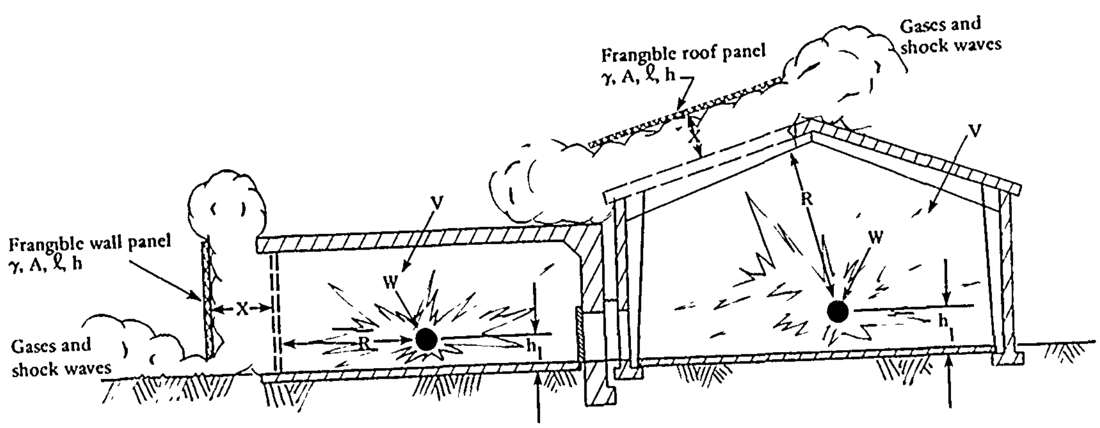


Figure 1. Frangible panels in Weapons Maintenance Facility.



Section A-A

Figure 2. Design parameters for frangible panels.

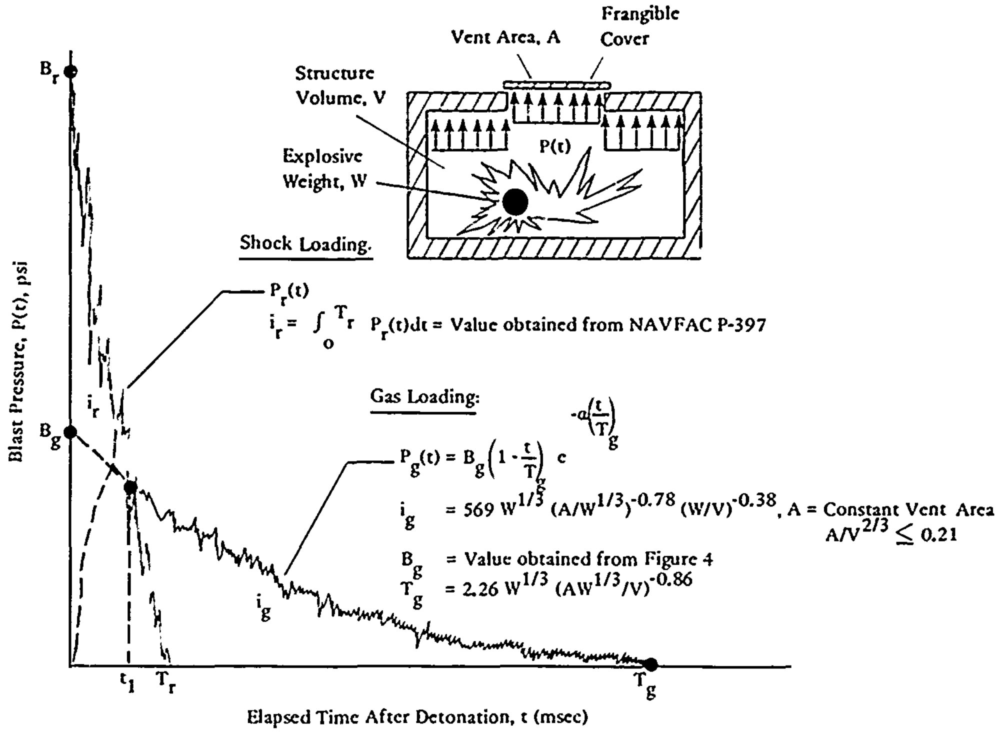


Figure 3. Internal blast loading for constant vent area; loading on a cover that is non-frangible for reflected-shock pressures but fully frangible for gas pressures.

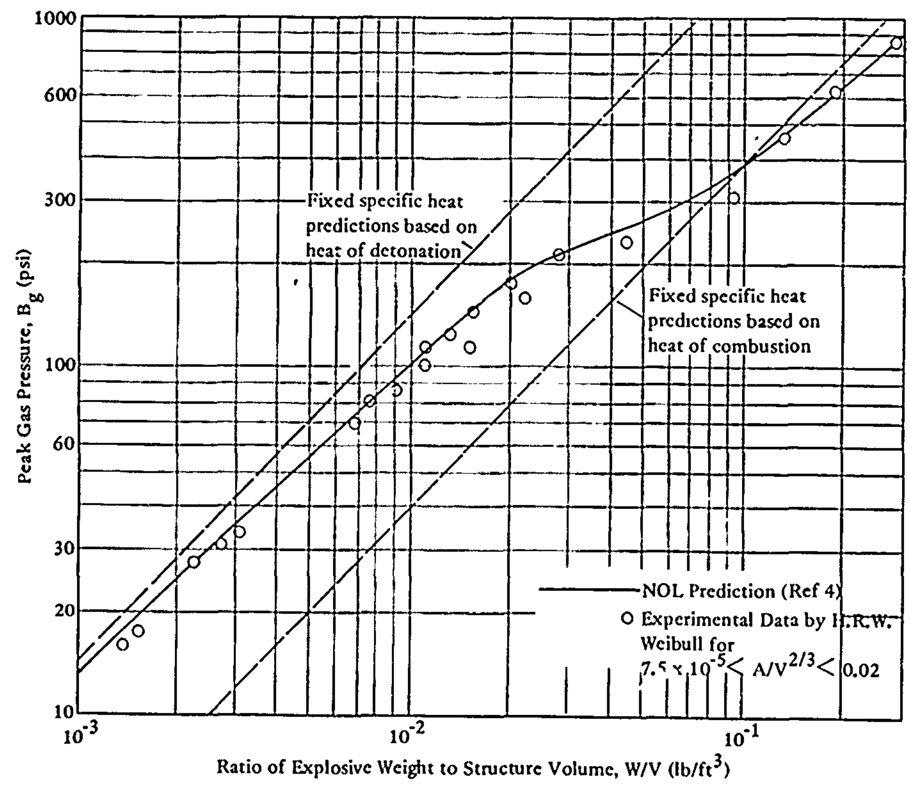


Figure 4. Peak gas pressure inside a structure.

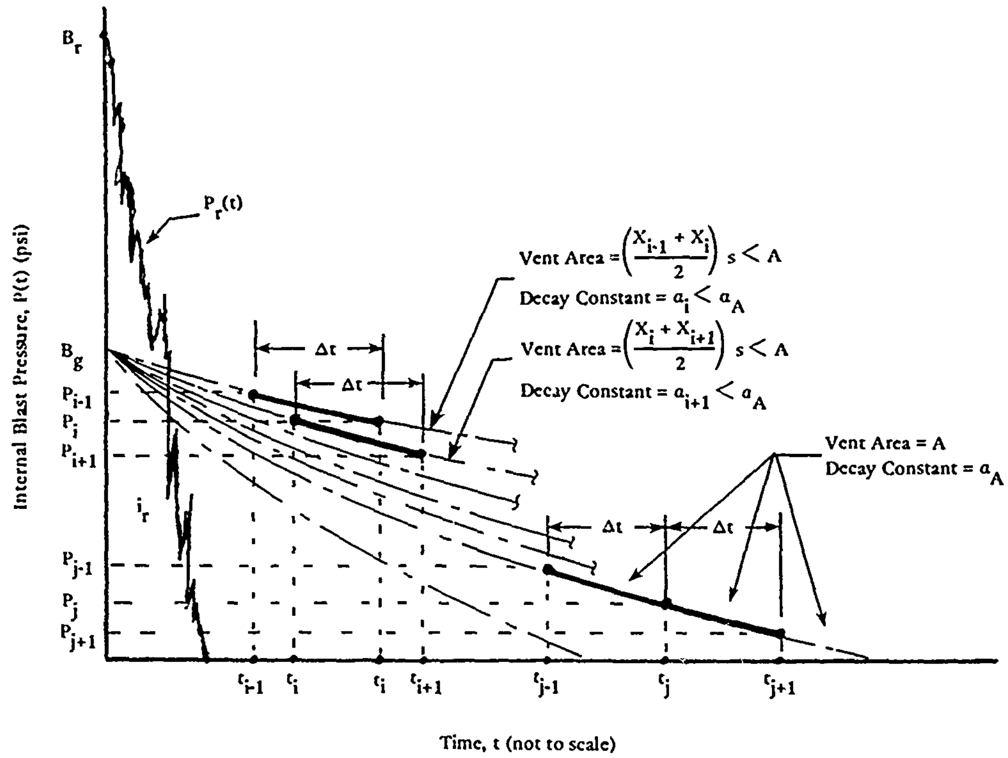


Figure 5. Graphical display of solution method for gas pressure history when response of cover controls venting and later when area of opening controls venting.

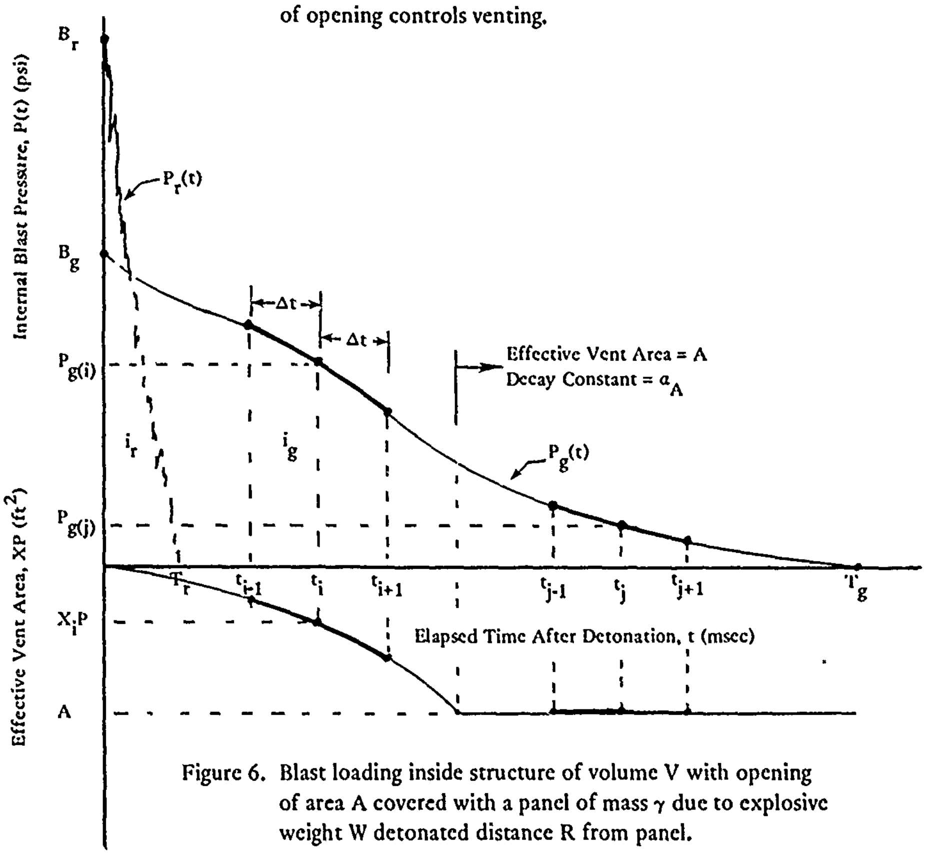


Figure 6. Blast loading inside structure of volume V with opening of area A covered with a panel of mass γ due to explosive weight W detonated distance R from panel.

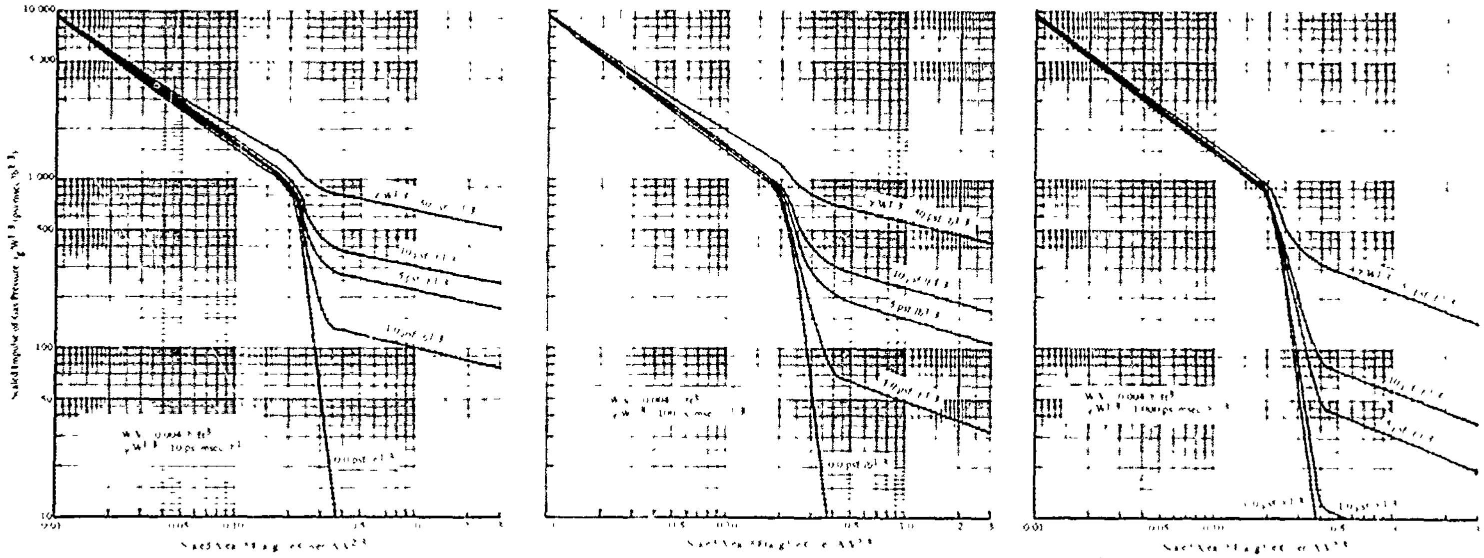


Figure 7. Design criteria for frangible covers for $W/V = 0.004\ lb/ft^3$.

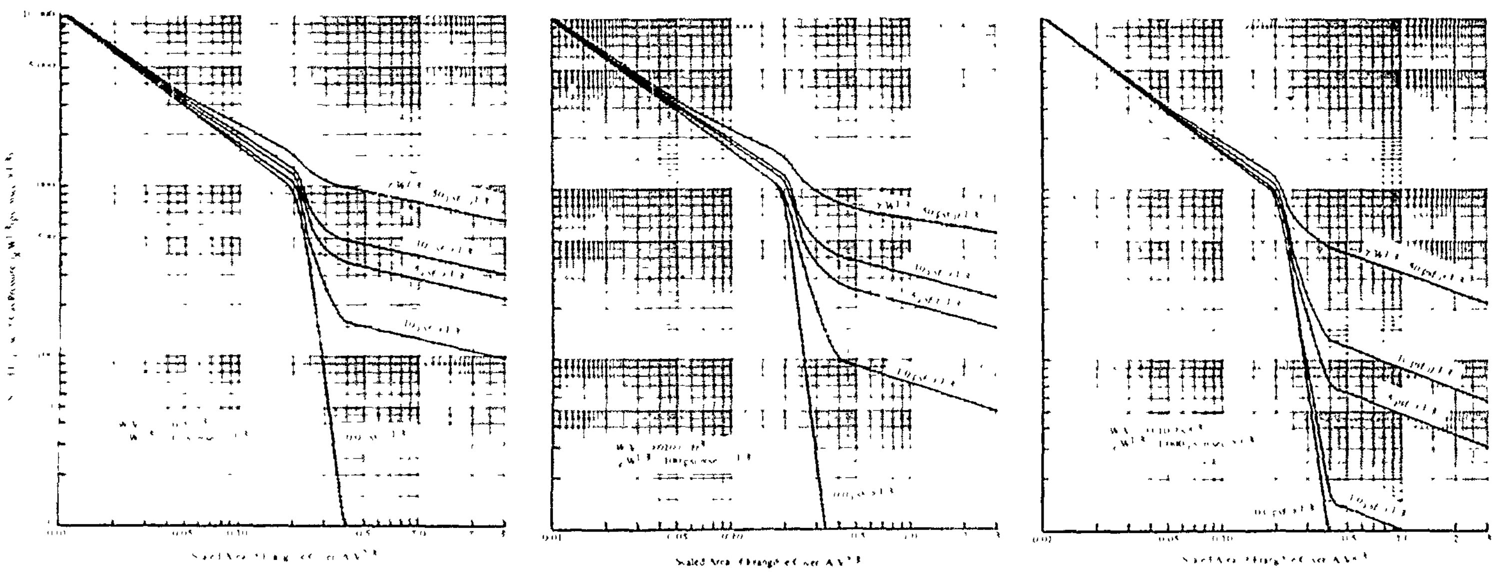


Figure 8. Design criteria for frangible covers for $W/V = 0.010\ lb/ft^3$.

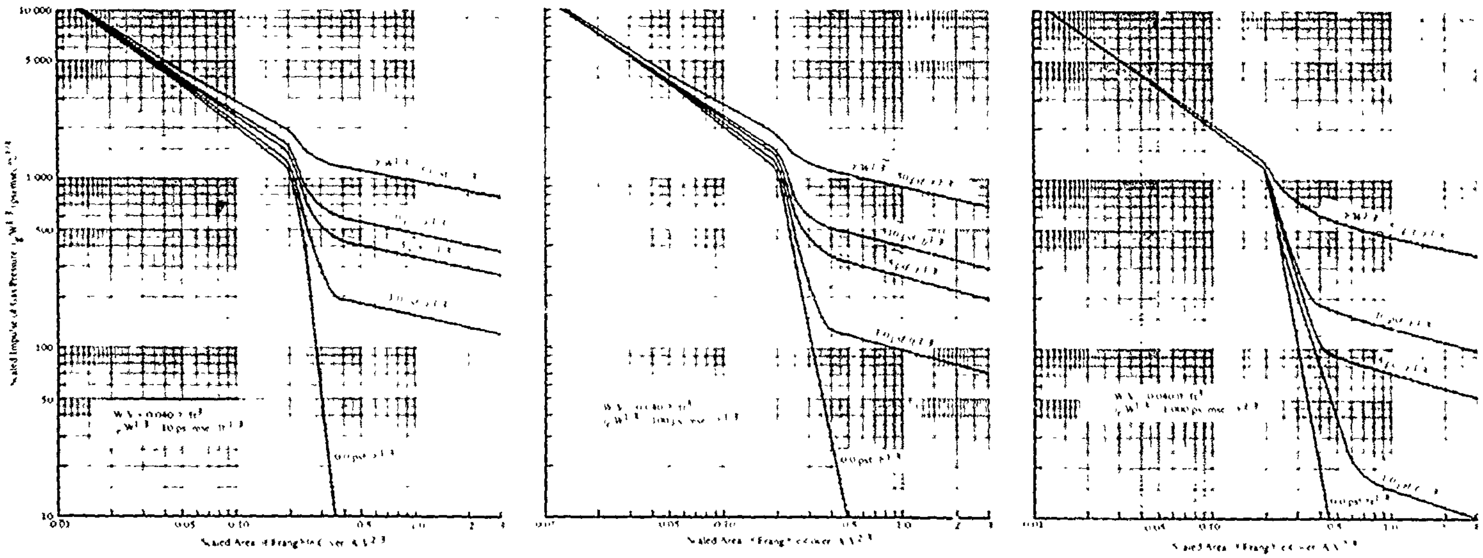


Figure 9. Design criteria for frangible covers for W/V = 0.040 lb/ft^3.

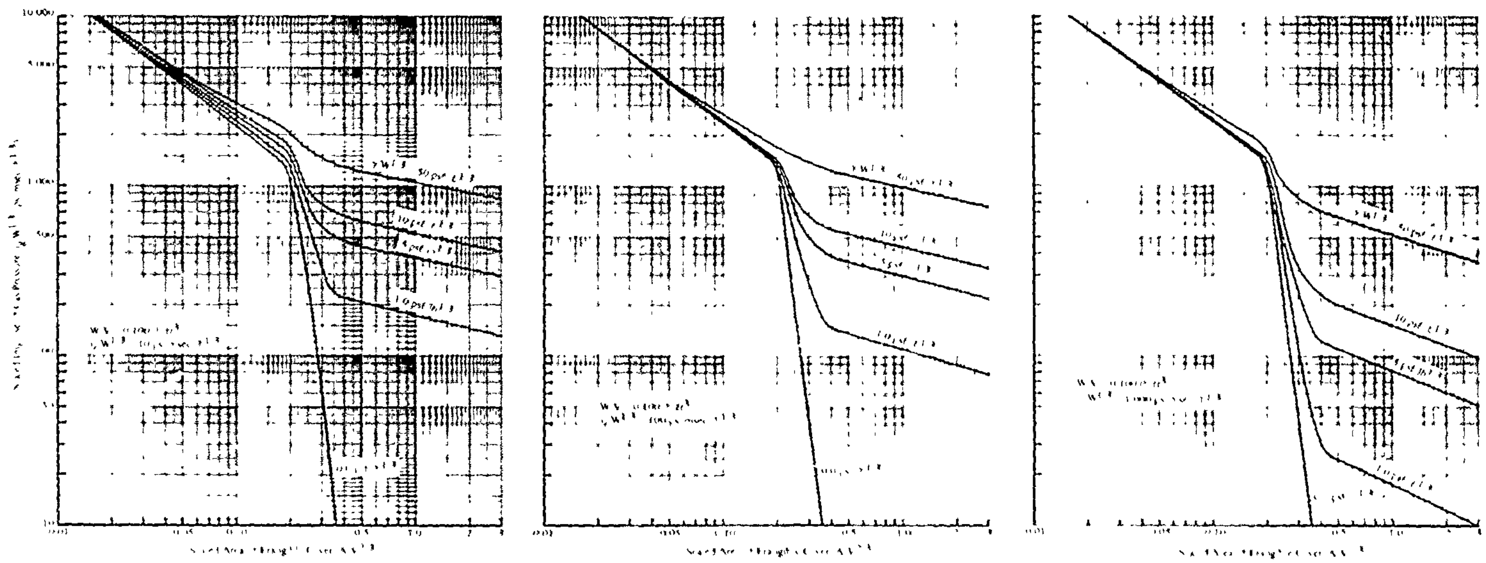


Figure 10. Design criteria for frangible covers for W/V = 0.100 lb/ft^3.

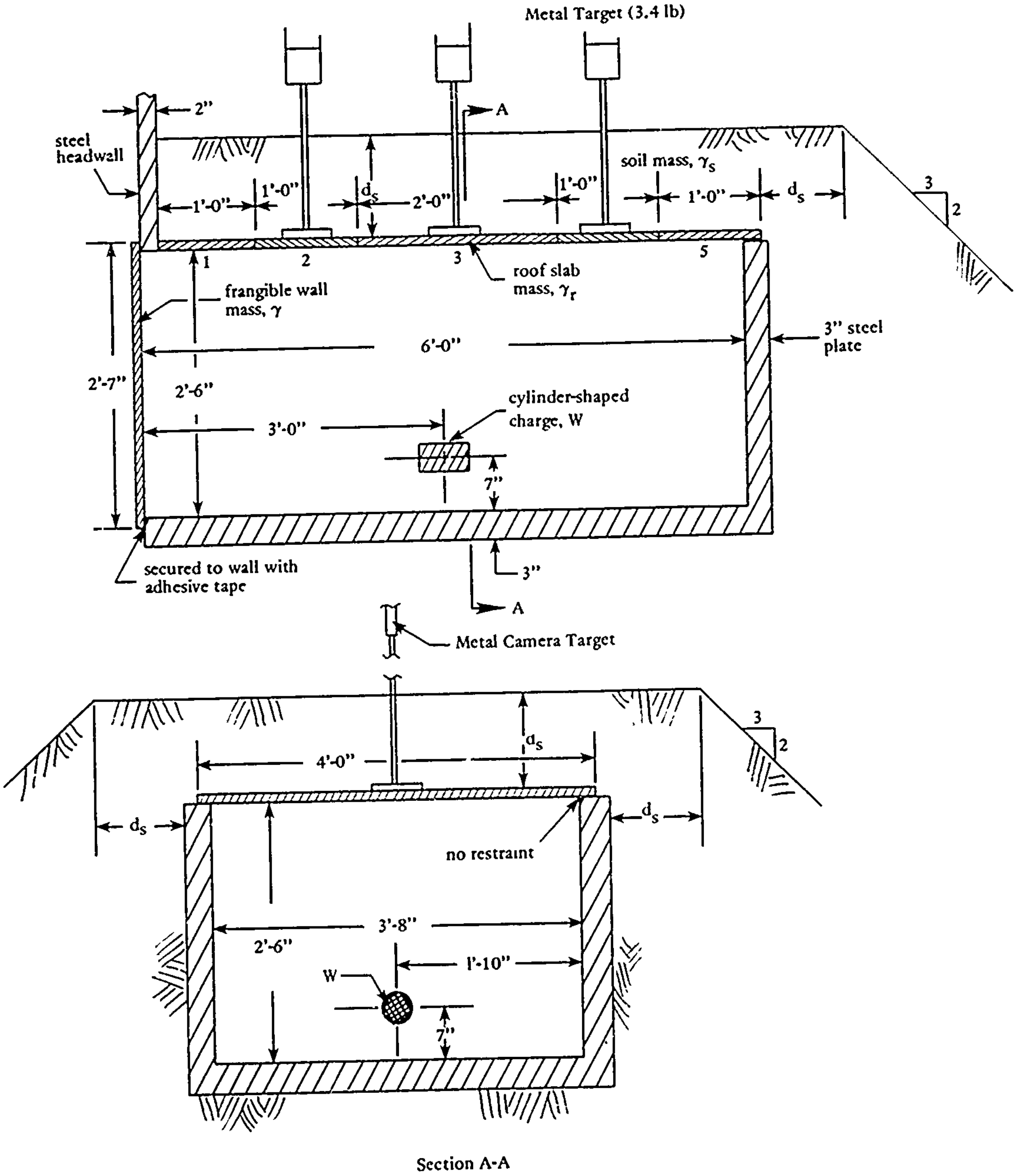


Figure 11. Design details of missile test cell.

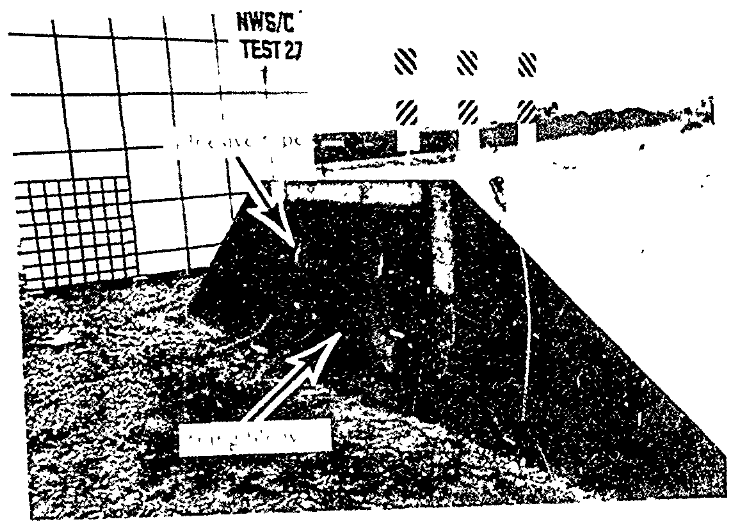


Figure 12. View of missile test cell.

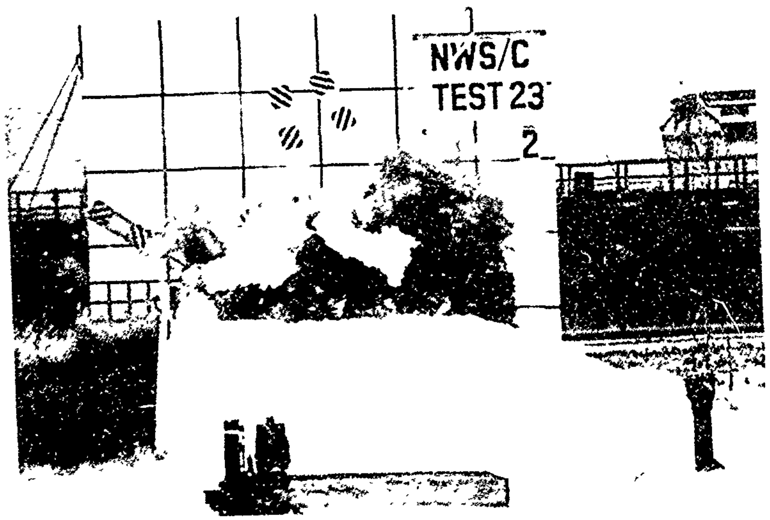


Figure 13. View of missile test cell near time of maximum response of roof slab - Test 23, no frangible wall (γ=0 psf), W = 1.0 lb.

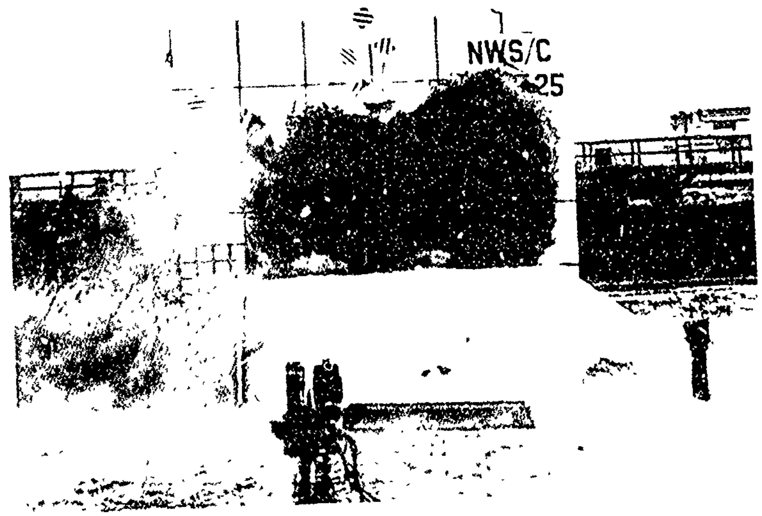
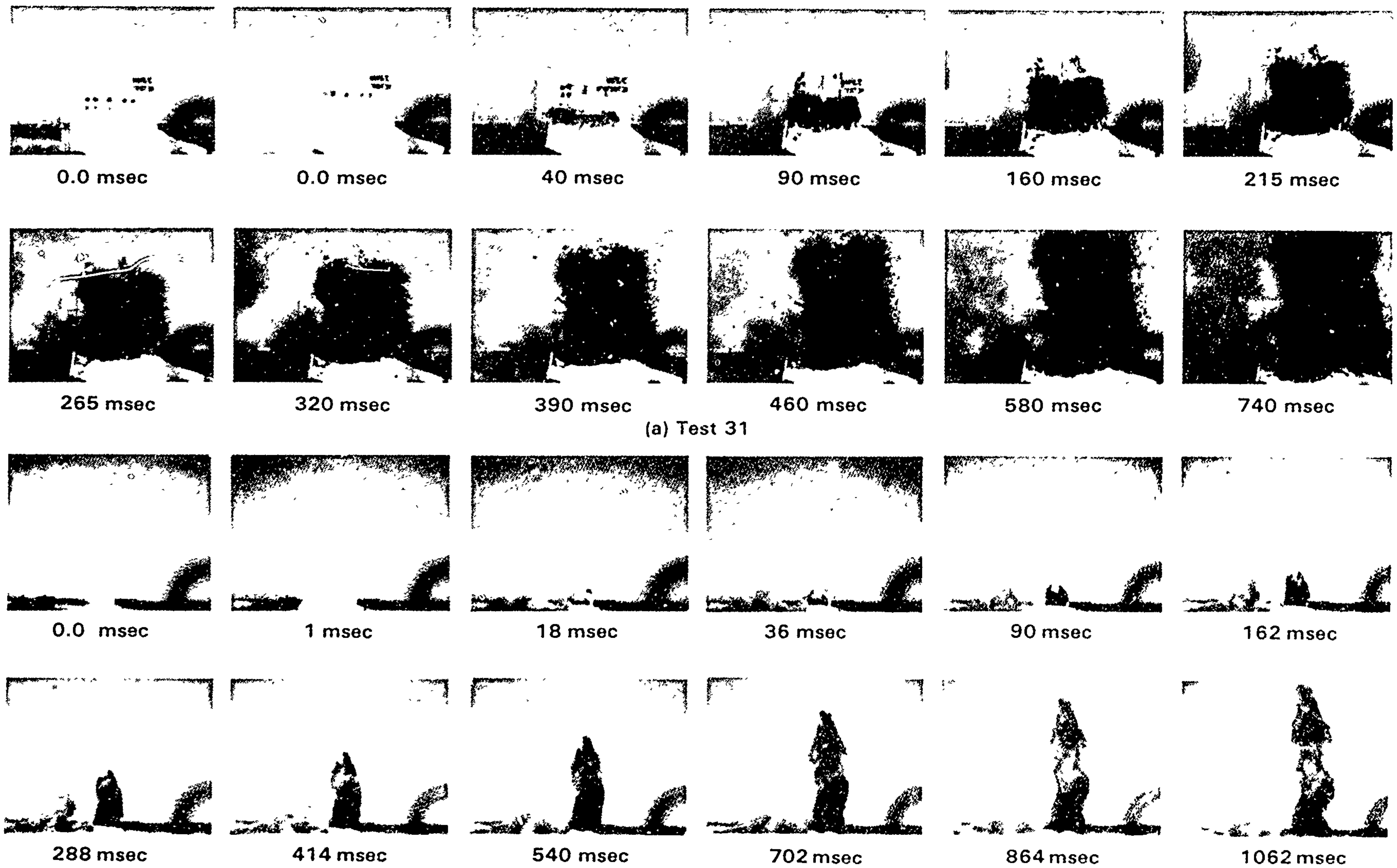


Figure 14. View of missile test cell near time of maximum response of roof slab - Test 25, plate glass wall (γ=1.73 psf), W = 1.0 lb.



(a) Test 31

(b) Test 33

Figure 15. Dissipation and directional effects of kinetic energy of roof mass